

# Extensive Air Showers and the Physics of High Energy Interactions

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Extensive Air Showers are still the only source of information on primary cosmic rays and their interactions at energies above PeV. However, this information is hidden inside the multiplicative character of the cascading process. In spite of the great experimental and theoretical efforts the results of different studies are often ambiguous and even conflicting. These controversies can partly be referred to imperfections of our models of high energy particle interactions.

The first part of the paper is concerned with this problem. The author thinks that the present models should be corrected to give slightly deeper penetration of the cascade into the atmosphere. In this respect the modification suggested by the QGSJET- II model seems to be the step in the right direction. The Sibyll 2.1 model provides a similar penetrating properties. However, this modification is not enough and a small additional transfer of the energy from EAS hadrons to the electromagnetic component is needed too. As a possible candidate for such a process the inelastic charge exchange of pions is discussed.

In the second part of the paper the author discusses the need to account for the interaction of EAS with the stuff of detectors, their environment and the ground in the light of the 'neutron thunder' phenomenon, discovered recently.

## 1. Introduction

There is a big progress in the analysis of experimental data on extensive air showers ( EAS ) during the last two decades. However, one cannot say that we understand all the phenomena and characteristics of EAS which we observe. Partly this dissatisfaction is due to the controversies in experimental data themselves, partly due to still remaining imperfections of the analysis. We certainly need to improve our understanding of EAS.

This paper does not aim to give a comprehensive review of all high energy interaction models, event generators and EAS simulation codes. It consists of two different parts. In the first part I point out some problems related to the particle interaction models which so far pose questions at high energies. I do not go into the theoretical foundations of various interaction models, but stay within a pure phenomenological approach. Within it I indicate the possible way to improve the models. The theoretical basis of some recent models can be found in [1].

In the second part of the paper I shall touch the problems related to some effects of the EAS

interaction with the environment.

## 2. High energy interactions

### 2.1. The consistency of the results

The EAS is a complex phenomenon - it has several different components: electromagnetic - electrons, positrons and gamma-quanta, muons and hadrons - nucleons, pions, kaons and so on. Besides that there are neutrinos which need massive detectors to be studied. Due to their small interaction cross-section they are detected not as multiple shower neutrinos, but as single ones. So far they are *not* combined with other EAS components in the analysis of experimental data, but they certainly play a role in the energy balance. Optical cherenkov and fluorescence photons emitted by charged shower particles are also used as a powerful tool for the study.

Since the characteristics of observed showers are the product of the primary cosmic-ray ( CR ) energy spectrum, mass composition and high energy interactions, the only way to disentangle them is to achieve the self-consistency in the derivation of the properties of primary CR from different observables and vice versa - the

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derivation of observed characteristics for different shower components and different observation levels from the same primary CR and the interaction model.

There were many efforts in the past to use models of the popular CKP- or scaling type. With the development of the QGS model [2] it has been shown that this model gives a satisfactory description of both EAS [3,4] and single, unassociated CR components in the atmosphere [5,6,7]. However, those old studies used as a rule different cascading algorithms and programs, which certainly produced an additional uncertainty in the results and reduced the credibility of the conclusions. It is to the credit of the KASCADE people who spend great efforts to develop and to distribute freely the CORSIKA code [8]. With this code the analysis of experimental data can now be made at the level much better than before.

## 2.2. The improvement of models

An early analysis of models indicated that the best consistency for the mean logarithmic mass  $\langle \ln A \rangle$  of primary CR derived from the  $\frac{N_\mu}{N_e}$  ratio and from  $X_{max}$  can be achieved for the QGSJET model [9]. Here  $N_\mu, N_e$  are muon and electron sizes of EAS respectively and  $X_{max}$  - the depth of the shower maximum. Later a similar conclusion about the preference of QGSJET model has been made on the basis of the analysis of the EAS hadronic core [10]. After some improvements the SIBYLL model, version 2.1 joined the list of the best, most popular and often used models [11].

However, the closer look reveals that some inconsistencies still remain. It has to be said that indications of possible inconsistencies appeared more than 30 years ago when the mismatch between the direct and indirect measurements of the primary energy spectrum has been noticed: the indirect measurements based on the EAS model calculations gave as a rule the higher CR intensity in the PeV region than that derived by the extrapolation of direct measurements from the lower energies - the so called 'bump' problem [12]. More recently this mismatch has been confirmed by [13]. Among possible explanations there was an assumption that even the best models give an overestimation of the primary energy from the ob-

servations in the atmosphere. It could happen if the shower penetrates deeper into the atmosphere and has more charged particles at the observation level than it is expected from model calculations.

Observations of the EAS cherenkov light in the PeV region confirmed this deeper penetration [14]. As a consequence, the primary mass attributed to such showers derived from observed  $X_{max}$  values and  $N_\mu/N_e$  ratio after the comparison with model calculations turned to be smaller than the true primary mass. There was a number of ideas how to increase the penetrability of the showers, for instance, introducing the higher cross-section for the charm production [15] or hypothetical strangelets [16,17], but those models are still in the stage of development. The possibility to improve the models were discussed also in [14,18]. In [14] it has been assumed that the cross-section and the inelasticity of the proton interactions in the air are in fact smaller than in the models, although they still agree with measurements at the lower end of the error bars. Their reduction allowed to improve the agreement between the predictions of the models and the results of the  $X_{max}$  measurements. There were some indications of the lower cross-sections in the past measurements of hadrons in the EAS cores [19]. The latest measurements of the inelastic cross-sections confirmed the slower rise of the interaction cross-section with energy [20,21]. Therefore, there are experimental indications that EAS may in fact penetrate deeper, than predicted by models.

There are also efforts to improve models not just on the pure phenomenological, but also on the theoretical basis. The idea that the density of partons at high energies becomes so high that they cannot interact independently of each other has been discussed long ago [22]. However, it is to the credit of S.S.Ostapchenko, who updated the QGSJET01 model including the non-linear effects of parton interactions, developed it to the status of the Monte Carlo event generator and together with his colleagues in Karlsruhe incorporated it into the Corsika code [23,24]. As a consequence of the non-linear effects, the interaction cross-section ( at least for pions ), the multiplicity of secondaries and the inelasticity of the collisions

decreased slightly which helped atmospheric cascades to penetrate deeper. Apparently the reduction of the inelasticity plays the major role in the increased penetrability. Due to its smaller inelasticity the updated Sibyll 2.1 model also provides EAS with a greater penetrability than previous models. Certainly these improvements are the step in the right direction.

However, the only introduction of the non-linear effects of parton interactions seems to be not enough. This suspicion appears when the examination of the hadron component is included into the analysis. It has been shown in [25] that the primary mass composition derived mainly from hadron and muon components is heavier than that which can be obtained using mainly electromagnetic and muon components. Muons are usually less model dependent at the fixed primary energy, since they are penetrating particles and are collected from all atmospheric altitudes representing something like an integral over the longitudinal profile of the shower. Taking them as the basis for the comparison we should expect that for well tuned, consistent models the analysis of ratios  $N_e/N_\mu$  and  $N_h/N_\mu$  should give the same  $\langle \ln A \rangle$ . The larger  $\langle \ln A \rangle$  value ( $2.25 \pm 0.08$ ) found in KASCADE experiment from  $N_h/N_\mu$  analysis than that from  $N_e/N_\mu$  ( $1.90 \pm 0.05$ ) [25] indicates that the difference between  $N_e/N_\mu$  and  $N_h/N_\mu$  in the present models is too low (Figure 1). In the more realistic model this difference should be increased.

The theoretical basis of QGSJET-II model besides the reduction of the interaction cross section for pions and an inelasticity requires also the reduction of the multiplicity of the secondary particles. Simulations of EAS showed that transition from QGSJET01 to QGSJET-II model at the fixed energy leads to the **rise** of  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios both for primary protons and for all primary nuclei. It is because the EAS electromagnetic and hadron components follow each other in the lower part of the atmosphere, i.e. beyond the shower maximum, in an approximate equilibrium. However, the difference between  $\langle \ln A \rangle$  values derived from  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios in the QGSJET-II model becomes even larger than for QGSJET01. While the  $\langle \ln A \rangle$  value derived from

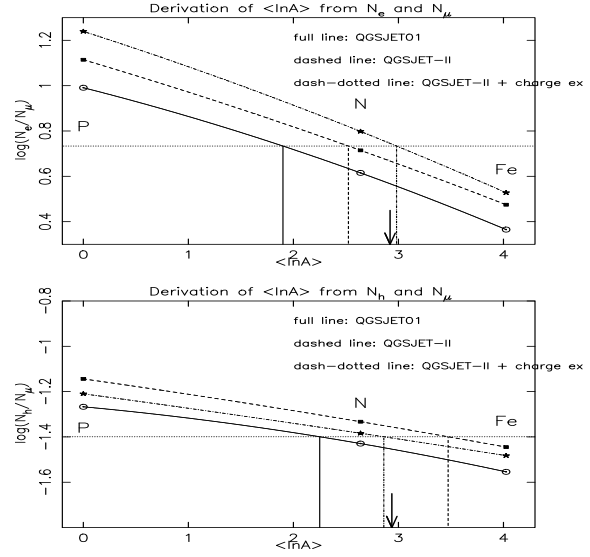


Figure 1. The illustration of the way to get the consistent value of mean logarithmic mass  $\langle \ln A \rangle$  from (a)  $N_e/N_\mu$  and (b)  $N_h/N_\mu$  measurements. Initial values of  $N_e/N_\mu$  and  $N_h/N_\mu$  are calculated for 1 PeV primary protons, nitrogen and iron nuclei using the QGSJET01 model and shown by the full line. The dashed line shows the same ratios for the QGSJET-II model:  $N_e/N_\mu$  and  $N_h/N_\mu$  rise by the same factor. The dash-dotted line demonstrates the effect of the charge exchange combined with the QGSJET-II:  $N_e/N_\mu$  rises, but  $N_h/N_\mu$  falls. The thick arrow indicates the consistent value of  $\langle \ln A \rangle$ .

$N_e/N_\mu$  ratio rises from 1.9 to 2.52, that derived from  $N_h/N_\mu$  rises from 2.25 to 3.47 (see Figure 1). Therefore, the reduction of the interaction cross-section for pions, of the inelasticity and the multiplicity in the QGSJET-II, does not remove the existing difference between  $\langle \ln A \rangle$  values and the inconsistency still holds.

To eliminate this inconsistency we have suggested the additional transfer of the energy into an electromagnetic component in the cascading process [18]. It has been made on a pure phenomenological basis. Later we have suggested the so called 'sling effect' in nucleus-nucleus interactions as the process responsible for a deeper penetration into the atmosphere of cascades induced

by primary nuclei and also for an additional electromagnetic component in them [26,27]. This effect could serve as a possible theoretical basis of the needed model modifications. However, this effect being very probable, seems to be small to give the noticable changes. The needed effect has to be stronger and we now think that the charge exchange process is the likely culprit.

In fact charge exchange processes are already taken into account in both QGSJET01 and QGSJET-II models. The question is whether it is possible to modify the probability of this process without a conflict with the existing experimental data and whether such a modification could give the consistent  $\langle \ln A \rangle$  value both from  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios.

In order to analyse this possibility I used the option provided by the HDPM model. It is the only model within the CORSIKA code where one can switch on and off the charge exchange processes and by this way to estimate the effect which this process has on  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios. Actually I determined the ratios  $R_{e\mu} = (N_e/N_\mu)_{HDPM+} / (N_e/N_\mu)_{HDPM-}$  and  $R_{h\mu} = (N_h/N_\mu)_{HDPM+} / (N_h/N_\mu)_{HDPM-}$  for the HDPM model with and without the charge exchange process (denoted as  $HDPM_+$  and  $HDPM_-$  respectively). Then I applied these ratios to the QGSJET-II model as  $\log(N_{e,h}/N_\mu)_{QGSJET-II+ch.exch.} = \log(N_{e,h}/N_\mu)_{QGSJET-II} + \varepsilon \log R_{e,h}$ . Here the coefficient  $\varepsilon$  limited by  $0 \leq \varepsilon \leq 1$  gives an estimate of possible increase of the charge exchange needed to get a consistent value of  $\langle \ln A \rangle$  derived from  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios, denoted as  $\langle \ln A \rangle_{e\mu}$  and  $\langle \ln A \rangle_{h\mu}$  respectively.

This exercise shows that by this way it is possible to achieve the needed consistency. Simulations show that inspite of the additional energy transfer the shower size at the sea level remains practically the same as in the absence of the charge exchange process, whereas the number of hadrons and muons decreased. So that in contrast to the modifications provided only by non-linear effects in the QGSJET-II model when both  $N_e/N_\mu$  and  $N_h/N_\mu$  rise, the increase of the charge exchange probability leads to the rise of  $N_e/N_\mu$ , but to the fall of  $N_h/N_\mu$ , because both

$N_\mu$  and  $N_h$  fall but the latter falls stronger. For example, with  $\varepsilon = 1$   $\langle \ln A \rangle_{e\mu}$  rises from 2.52 to 2.98, but  $\langle \ln A \rangle_{h\mu}$  falls from 3.47 down to 2.86 (see Figure 1). This 'overshooting' is due to that the charge exchange process is already taken into account in the QGSJET-II model and application of the expression given in the previous paragraph with  $\varepsilon = 1$  makes this process too strong. The consistent value of  $\langle \ln A \rangle_{e\mu} = \langle \ln A \rangle_{h\mu} = 2.94 \pm 0.09$  is achieved at  $\varepsilon = 0.88 \pm 0.12$ . The errors are derived from the statistical errors of mean values of  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios obtained by Monte-Carlo simulations with CORSIKA6.014 and CORSIKA6500 codes and taking the values of  $\langle \ln A \rangle_{e\mu} = 1.90 \pm 0.05$  and  $\langle \ln A \rangle_{h\mu} = 2.25 \pm 0.08$  obtained from the experimental data using the QGSJET01 model [25]. Systematic errors are difficult to evaluate at this stage of analysis, but actually our estimates are given just to demonstrate the principal opportunity to use the QGSJET-II model with an enhanced charge exchange probability to get a consistent estimates of the primary CR mass composition.

The higher consistent value of  $\langle \ln A \rangle = 2.94 \pm 0.09$  compared with values of  $1.90 \pm 0.05$  and  $2.25 \pm 0.08$  derived from  $N_e/N_\mu$  and  $N_h/N_\mu$  ratios with the QGSJET01 model means that the true primary CR mass composition should be heavier in the new analysis.

Simulations show also that with the increased charge exchange the depth of maximum for proton induced showers shifts upwards by about 5  $\text{gcm}^{-2}$ , but for nitrogen and iron induced showers it moves downwards by 1  $\text{gcm}^{-2}$  and 5  $\text{gcm}^{-2}$  respectively. Hence the increase of the charge exchange cannot destroy the deeper penetration of EAS by about 20  $\text{gcm}^{-2}$  provided by the QGSJET-II model.

### 2.3. The inelastic charge exchange for pions

Now we shall discuss the process which could be used to increase the charge exchange probability. At the end of sixties one of the inventors of the ionization calorimeter, V.S.Murzin from the Moscow University used this detector to study interactions of CR pions. He has found that with a considerable probability the charged pion could

lose its charge but preserve a good part of its initial energy. He called this process 'the inelastic charge exchange' [28]. Actual numbers were the following: the probability to preserve more than 0.5 of the energy in the collision of the pion with iron nuclei has been estimated as 10% and this probability seemed to be independent of energy in hundred GeV - TeV energy range.

Since then numerous experiments have been made on the production of neutral pions in hadron interactions. Their results can be found in the Particle Data Group archive (<http://durpdg.dur.ac.uk/HEPDATA/react.html>) (see also the list of literature in [29]). However, measurements of collisions with nuclei are still sparse and cover mostly the high transverse momentum ( $P_t$ ) region. The relevant data relate mostly to  $\pi^\pm P$  interactions and often give the values of invariant cross-sections [29,30,31,32,33,34]. After integrating over  $P_t$  some extreme examples [30,31,33] of the obtained inclusive spectra for neutral pions are shown in Figure 2.

It is seen that the results of different experiments have a considerable spread. While the result of one experiment matches the model perfectly [33], the  $\pi^0$ -spectrum obtained in another experiment follows the spectrum of  $\pi^+$  [30] and there is a spectrum which is definitely higher than that which matches the model [31] although they agree with each other within error bars. This difference cannot be caused by the energy dependence of the process since models and experiments show no appreciable dependence in the 58 - 360 GeV energy interval [34]. The examination of these data indicates that the probability to have  $\pi^0$  with  $X > 0.5$  is not 10%, but about 7% at these energies and for  $X > 0.7$  it is about 2.3%.

It seems that on the basis of the spread of experimental data and the absence of the preference between the different results the model can be retuned according to indications of the EAS analysis towards the higher probability of the charge exchange process for pions. This can improve the consistency between  $\langle \ln A \rangle$  values obtained from different EAS components. Since at  $X > 0.7$  the difference between different experiments rises up to  $\sim 2.5$  and continues growing with  $X$ , the big value for the estimate of  $\varepsilon = 0.88 \pm 0.12$ , pre-

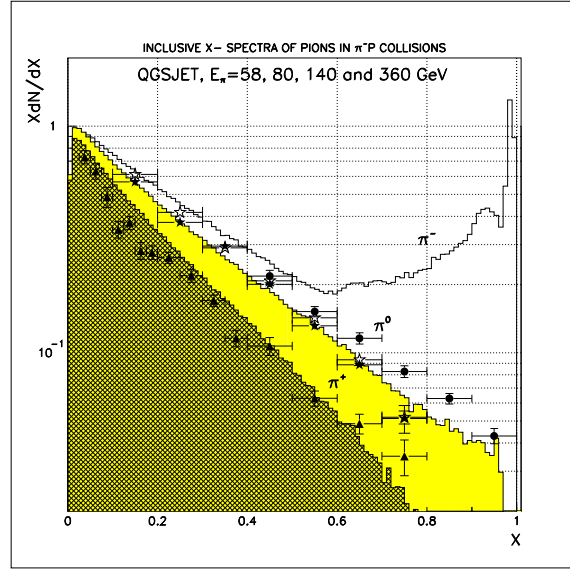


Figure 2. The inclusive spectrum of neutral pions produced in  $\pi^- P$  interactions. Full circles - for the 58 GeV  $\pi^-$  beam energy [31], open and full stars - for 80 and 140 GeV respectively [33], triangles - for 360 GeV [30]. Horizontal error bars indicate the interval of  $X$  used for the determination of the invariant cross-section. Histograms are spectra of  $\pi^+$ ,  $\pi^0$  and  $\pi^-$  calculated with CORSIKA INTTEST version for the QGSJET01+GHEISHA interaction model at 80 GeV. The use of the QGSJET01 model at this energy is justified since non-linear effects introduced in QGSJET-II appear at much higher energies.

sented in the previous subsection, is not inconsistent with these experimental data.

There is another point which should be remarked. The appearance of leading neutral pions in charged pion collisions observed in cosmic-ray and in some of accelerator experiments is interpreted within the framework of the triple-region description with a substantial contribution of RRP-term. Its contribution should give the flat behaviour of the inclusive  $\pi^0$  cross-section at large  $X > 0.7$ . It is not seen in the data shown in Figure 2. This discrepancy is not clear. However, it can be that  $\pi^0$ 's with very large  $X$  are biased in accelerator experiments by triggering conditions, with partially suppressed low multiplicity

and diffraction events as has been mentioned in [30], while the introduced corrections are model dependent. There was no such bias in cosmic-ray experiments.

The experimental value of the mean fraction  $\alpha_\gamma$  of energy transferred by  $\pi^-$  to  $\pi^0$  is independent of energy and equal to  $0.25 \pm 0.01$  [28]. The  $\alpha_\gamma$  provided by the QGSJET01 model shows a slight decrease with the energy and above 10 TeV falls below the experimental value ( Figure 3 ). Independently of the origin of this fall ( e.g. change of the mass composition of secondaries ) it is another indication that the energy transfer into the electromagnetic component should be slightly increased to improve the model.

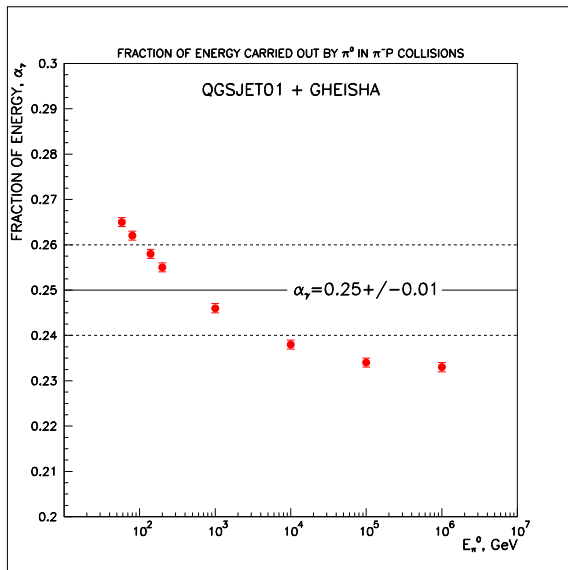


Figure 3. The mean fraction of energy  $\alpha_\gamma$  transferred to neutral pions in  $\pi^- P$  collisions as a function of energy. The experimental value of  $\alpha_\gamma = 0.25 \pm 0.01$  is from [28] and denoted by full and dashed lines. The full circles show  $\alpha_\gamma$  values calculated with the QGSJET01+GHEISHA model. The calculated values are slightly smaller than experimental ones above 10 TeV.

### 3. Interactions of EAS with detectors and an environment

The second part of this paper relates to interactions of EAS particles not with air nuclei, but with another target: the stuff of the detectors, their environment and the ground. The aim of this part is to draw an attention to the possible contribution of low energy neutrons created in such interactions to the signal in the hydrogen containing detectors, deployed particularly at mountains.

It is well known that the thickness of the shower disk depends on the distance from the shower core rising from 2-3 m at the EAS center to tens of m at about 1 km from it. It corresponds to the time 'thickness' of a few hundreds ns. The delayed particles which appear a few microseconds after the main shower front were observed and discussed long ago [35,36,37]. However, the discovery of neutrons delayed by *hundreds* microseconds in the shower core made by Chubenko A.P. and his group with the Tien-Shan neutron monitor [38,39,40,41,42] seemed to be unexpected and attracted an attention [43,44,45,46,47].

Though the dispute on the interpretation of this finding is not finished the majority of participants is inclined to explain it by the interaction of hadrons in the EAS core with the stuff of the detector, i.e. by multiplicative processes in the lead of the neutron monitor with the subsequent long diffusion and thermalization of released neutrons in the monitor's moderator and reflector [47,48,49] ( see, however, another view in [50] ). Independently of the interpretation the phenomenon is very spectacular and looks as the neutron 'thunder' which appears with a time delay after the 'lightning' which is the EAS itself [49,51].

If the interpretation of the majority is correct, the observed neutrons can be produced also in the ground which is not so heavy as lead, but nevertheless there are many heavy elements in it ( mainly Si ) which could produce neutrons being hit by an EAS core. There is also water in it which serves as a good moderator like in nuclear reactors. The influence of the ground and ground-based environment has to be more sub-

stantial at the mountain level, where EAS cores are much more energetic and a good part of the year the ground is covered by snow. Sometimes this snow is of meters thick ( Tien-Shan, Aragats, Chacaltaya, South Pole etc. ). As for the Tien-Shan station an additional factor is that it is built on the permafrost with a good part of ice in it. Since neutrons can diffuse up to long distances from the place where they are produced [52] their effect might be noticeable even at shallow depths underground.

Many running EAS arrays use water or ice cherenkov detectors: Pierre Auger Observatory, Milagro, Nevod, Ice-Top etc. At the first sight they should not be sensitive to neutrons, since they are neutral particles and mostly non-relativistic. However, the experimental study of the neutron 'thunder' revealed that delayed neutrons are accompanied by gamma-quanta and electrons [41], which in principle could give a signal in water tanks.

It is particularly relevant to Pierre Auger Observatory. The comprehensive modelling of the effect of albedo neutrons emitted by the ground as a result of the EAS interaction is complicated and planned for the future paper. Here I show that the effect can be noticeable even taking into account only EAS neutrons.

Simulations of the EeV proton induced showers observed at the altitude of 1400 m a.s.l. show that neutrons are the most abundant among EAS hadrons and their lateral distribution function ( LDF ) is wider than LDF for protons and pions. At the typical distance of  $\sim 1$  km from the core the density of neutrons with energy above 50 MeV and their energy density is about the same as for muons of this energy and about 10% of the gamma-quanta plus electrons with energy above 1 MeV ( Figure 4 ).

Moreover after about  $5 \mu s$  behind the EAS front the neutron component at 1 km from the EAS axis becomes dominant, overtaking muons, electrons and gamma-quanta ( Figure 5 ).

This distance and the time delay are right the working distances and times for Pierre Auger Observatory, so that the possible contribution of neutrons to the signal from their water tanks should be analysed and taken into account if nec-

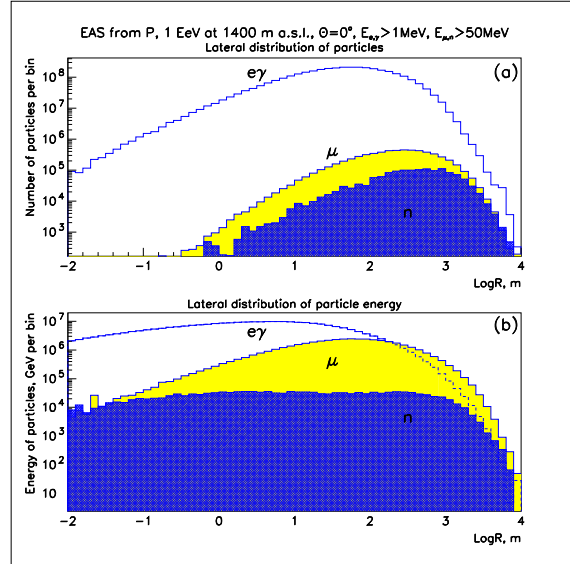


Figure 4. Lateral distribution of particle numbers (a) and the particles energy (b) for 1 EeV primary proton incident vertically at the level of 1400 m a.s.l. It is seen that neutrons could contribute up to 10% to the signal of water tanks at 1km distance from the shower axis, if among products of their interaction with water are relativistic electrons.

essary. The same remarks could be referred to hydrogen containing plastic scintillators used in many other large arrays ( Yakutsk, Telescope Array etc. ). As it has been mentioned above, signals delayed by  $\mu s$  ( 'subluminal pulses' ) have been already observed in large scintillator arrays, such as Volcano Ranch [36,37].

A good analysis of the possible effect of delayed particles on the primary energy estimation has been made in [53] applicable to the AGASA array. It has been shown that overestimate of the primary energy for its scintillators and the acquisition system cannot exceed a few percents. For other arrays it may be higher.

Presumably the effect of 'the neutron thunder' can be applied in practice for the neutron carotage of the upper layers of the ground. Instead of the artificial neutron source in this method the ordinary EAS can be used since EAS cores carry



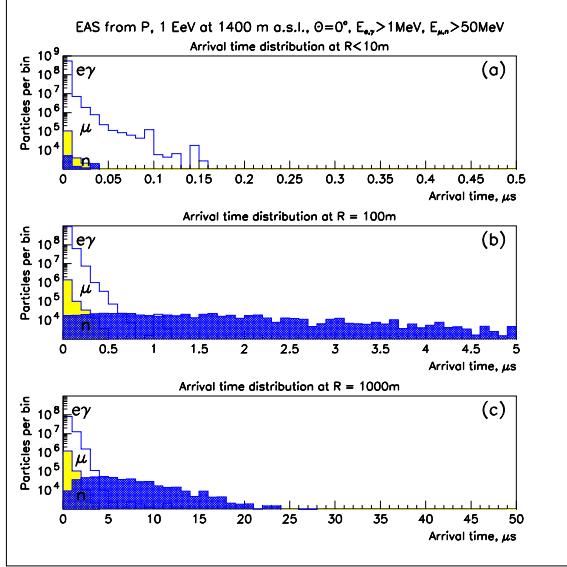


Figure 5. Arrival time distribution of electromagnetic, muon and neutron component of the shower at core distances less than 10m (a), 100m (b) and 1000m (c). It is seen that at 1000m from the core neutrons dominate among other particles after 5  $\mu$ s.

on and produce a lot of secondary neutrons. Also 'the neutron thunder' can be used for the search of water on the Moon [54] or on the surface of other planets [55,56].

#### 4. Conclusion

The analysis of existing controversies in the interpretation of experimental data on EAS indicates that an improvement of our understanding of the EAS phenomenon and the self-consistency of results on primary CR derived from EAS can be achieved by a moderate modification of the current particle interaction models. This modification has to result in a slightly deeper penetration of EAS into the atmosphere as well as in the increased transfer of the energy from the hadronic to electromagnetic components of EAS. The account for non-linear effects in parton interactions like that in the QGSJET-II model and an increasing probability of inelastic charge ex-

change processes for pions can help.

Here it is appropriate to make some general remarks. The nuclear and electromagnetic nature of EAS has been established at the end of forties. That was the time when the world greatest accelerator - Dubna Synchrophasotron had not been commissioned and CR were the unique source of information about high energy interactions. It is surprising that now, after about 50 years of the leading role of accelerators in the field, CR are still able to contribute to our understanding of the high energy interactions. Another point is that after nearly 70 years since the discovery of EAS by Pierre Auger and Roland Maze we still develop our understanding of this phenomenon. The discovery of the 'neutron thunder' certainly complements our knowledge of the EAS development and is worth of further experimental and theoretical study.

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